# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4314

## ICING FREQUENCIES EXPERIENCED DURING CLIMB AND DESCENT BY FIGHTER-INTERCEPTOR AIRCRAFT

By Porter J. Perkins

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
July 1958

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4314

# ICING FREQUENCIES EXPERIENCED DURING CLIMB AND DESCENT BY FIGHTER-INTERCEPTOR AIRCRAFT

By Porter J. Perkins



## SUMMARY

Data and analyses are presented on the relative frequencies of occurrence and severity of icing cloud layers encountered by jet aircraft in the climb and descent phases of flights to high altitudes. Fighter-interceptor aircraft operated by the Air Defense Command (USAF) at bases in the Duluth and Seattle areas collected the data with icing meters installed for a 1-year period. The project was part of an extensive program conducted by the NACA to collect icing cloud data for evaluating the icing problem relevant to routine operations.

The average frequency of occurrence of icing was found to be about 5 percent of the number of climbs and descents during 1 year of operations. The icing encounters were predominantly in the low and middle cloud layers, decreasing above 15,000 feet to practically none above 25,000 feet.

The greatest thickness of ice that would accumulate on any aircraft component (as indicated by the accretion on a small object) was measured with the icing meters. The ice thicknesses on a small sensing probe averaged less than 1/32 inch and did not exceed 1/2 inch. Such accumulations are relatively small when compared with those that can form during horizontal flight in icing clouds. The light accretions resulted from relatively steep angles of flight through generally thin cloud layers.

Because of the limited statistical reliability of the results, an analysis was made using previous statistics on icing clouds below an altitude of 20,000 feet to determine the general icing severity probabilities. The calculations were made using adiabatic lifting as a basis to establish the liquid-water content. Probabilities of over-all ice accretions on a small object as a function of airspeed and rate of climb were computed from the derived water contents. These results were then combined with the probability of occurrence of icing in order to give the icing severity that can be expected for routine aircraft operations.

INTRODUCTION

Routine flying at high altitudes (above 20,000 ft) has proven that adverse weather conditions, including icing, are generally not as severe as those experienced at lower levels. However, the extent to which icing protection can be reduced or eliminated for high-altitude aircraft may depend on conditions encountered during phases of flight other than those at high-altitude cruise. The icing problem for high-altitude aircraft can be considered in three phases: icing encountered during cruise at high altitudes, icing encountered during climb and descent, and icing encountered during approach. In this report only the climb and descent phase of the problem is studied with the knowledge that these parts of the flight are subject to the greater frequency and intensity of icing clouds that exist below an altitude of 20,000 feet. Measurements of supercooled clouds at these lower levels have been conducted by the NACA (ref. 1) and others concerned with the icing problem. The extent to which these conditions are a problem for high-altitude aircraft are evaluated in this report for routine flight operations.

4699

The frequency and severity of icing depend upon conditions of cloudiness, temperature, and liquid-water concentration that are present at any given altitude. Above 20,000 feet the over-all reduction of heavy cloud cover results in less frequent icing conditions than occur at lower altitudes. The colder temperatures associated with high altitudes further reduce the frequency of icing. This is evident from the results of an earlier study (ref. 2), wherein the relative frequency of icing existing in all the clouds penetrated was found to decrease rapidly with decreasing temperature. As the temperature is lowered, the probability increases for the liquid-water droplets to change to ice crystals, which do not generally adhere to aircraft surfaces. The severity of icing in layer-type clouds can be expected to be less at high altitudes also because of the colder temperatures. The water vapor available for condensation decreases with temperature and is further lowered because of the limited vertical displacement, which characterizes the formation of stratoform clouds. The tendency toward cystallization also reduces the liquid-water content available for ice formations.

In contrast to the expected low liquid-water content available in layer-type clouds at high altitudes, cumulonimbus clouds (thunderstorms) can produce severe icing because of large water contents derived from the extensive vertical development of this type of cloud. Excessive liquid-water contents (up to 5 g/cu m) have been calculated on the basis of adiabatic lifting (ref. 3). Statistical data for the investigation of this problem have been impossible to obtain since the general flight practice has been to avoid penetration of cumulonimbus clouds as much as possible during routine operations at high altitudes.

A program has been conducted by the NACA Lewis laboratory to obtain extensive icing-cloud data in order to guide the manufacturer and operator in the design and operation of icing-protection systems. As a part of this program, a project was conducted in cooperation with the U.S. Air Force to measure the frequency and severity of icing experienced during climb to and descent from high altitudes. Jet fighter-interceptor aircraft operated by the Air Defense Command were chosen for the program because of their frequent and extensive vertical traverses. Appreciation is extended to this branch of the U.S. Air Force and the individual pilots for their cooperation in collecting and reporting the special data necessary for this study.



This report presents the frequency and an indication of the severity of icing conditions encountered during the climb and descent of jet fighter-interceptor aircraft equipped with icing-rate meters operating from bases in the Duluth, Minnesota, and Seattle, Washington, areas for a 1-year period. The limited period of the survey prevented a sufficient accumulation of data to evaluate adequately the probabilities concerning icing conditions, and in particular, the icing severity. Consequently, probabilities of icing severity are calculated using previous statistics on icing clouds below an altitude of 20,000 feet.

## DESCRIPTION OF AIRCRAFT OPERATIONS AND INSTRUMENTATION

The jet-fighter aircraft that were instrumented for this project were flown in routine missions from the two Air Force bases, which were chosen to provide a range of climatic conditions in the survey. Duluth, Minnesota, represented a mid-continent region frequented by polar continental air masses (modified, at times, by the local influence of the Great Lakes); Seattle corresponded to a coastal area subject to the influence of maritime air masses. About three-fourths of the flights were interception-type missions. The remainder were flown for training and test purposes. In all missions the aircraft climbed directly to high altitudes and usually returned to base in less than 2 hours after takeoff. Airspeed and rate of climb varied over a wide range during the climbs and descents. Weather was not a factor in mission planning except in cases where flights could be delayed when subminimum conditions existed at the base.

Five aircraft at each base were equipped with NACA pressure-type icing-rate meters (described in ref. 4) to measure and record ice that formed on a small sensing probe when the aircraft passed through an icing-cloud layer. The ice was measured by means of a pressure-sensitive system, which responded to the blocking of small total-pressure holes in the leading edge of a 0.1-inch-diameter tube. At a given ice thickness (0.028 in.) the resulting pressure drop through the holes actuated an electrical de-icing system. When the holes became ice-free, the heating

was stopped and the ice buildup was repeated. The rate of accretion was measured by recording the time required to obtain the given ice thickness. Adding these thicknesses for a number of cycles gave a cumulative ice thickness that would have formed on an unheated probe while in the icing cloud. The probe was mounted normal to the airstream and near the nose of the aircraft about 7 inches out from the fuselage (fig. 1). Associated equipment mounted inside the aircraft operated automatically when icing was encountered and recorded on film the icing time for each cycle along with altitude, indicated airspeed, and temperature. An indicating light
installed in the cockpit informed the pilot when ice was detected by the 4699
probe.

In order to supplement the recorded information, a special log of every flight of the instrumented aircraft was requested of the pilot. These forms, shown in figure 2, were supplied by the NACA. The data included an identification of the flight and notations as to the occurrence or nonoccurrence of icing and/or cloud penetrations during the flight. An approximate description of the flight path on a time-altitude grid printed on the form provided an indication of the altitude range surveyed during each flight. The data were reported continuously for 1 year, which covered the period from August, 1955, through June, 1956, at Duluth and from November, 1955, through September, 1956, at Seattle.

## RESULTS AND DISCUSSION

### Results from Fighter-Interceptor Aircraft Operations

Data obtained from the climbs and descents of the jet-fighter aircraft operating in the surveyed areas are presented in tables I and II. In table I the total number of flights, cloud penetrations, and icing encounters are listed for both areas along with the resulting icing frequencies. The results are organized in groups to show the effect of seasonal variations in temperature. The climbs and descents in which the ice accretions were measured are given in table II.

Icing frequencies. - The frequencies of icing encounters based both on the number of flights and on the number of clouds penetrated (table I) are derived from the experience of the fighter-inteceptor aircraft over a survey period of only 1 year. The icing frequencies are associated with the complete flights rather than with the separate climbs and descents. The usual short duration of a flight (less than 2 hr) did not give a sufficient time separation between the climb and descent to make them independent because of the general persistence of clouds and icing conditions. The frequency of icing encounters based on the number of clouds penetrated represents the fraction of the clouds penetrated that contained supercooled liquid water. The clouds that did not produce icing were either at air temperatures too high to cause icing on the probe or were composed of ice crystals that do not generally adhere to unheated surfaces. Since only 1 year of observations was covered, the icing frequencies do not represent long-term averages. The frequency of occurrence of the meteorological factors associated with icing can vary considerably from one year to another in any given area.



Icing frequencies varied among the seasonal groups from 0 to 9 percent of the flights. Low icing frequencies (0 to 3 percent) were experienced during the summer months in both areas. Higher icing frequencies (up to 9 percent) were prevalent in both areas during the winter, spring, and fall. An over-all icing frequency of 5 percent (59 encounters in 1174 flights) was found for year-round operations in both areas. It should be noted that these data are associated with the particular flight practices and are, therefore, not necessarily an unbiased sample of the range of conditions that existed in the atmosphere. Flights and flight planning may have been altered on certain occasions to avoid passing through cloud layers or known or suspected areas of icing. The relative frequencies could be significantly influenced if a flight path were chosen through holes or breaks in the clouds. However, the flight procedures used with these aircraft would appear to reduce this bias somewhat. Interception flights, ground-controlled or otherwise, usually penetrated clouds that existed in the flight path. The pilots felt that the rapid climbs and descents made through cloud layers would allow only a small amount of ice to collect, which would not be enough to affect the operation or performance of the aircraft.

Frequency distribution of icing encounters with altitude. - The frequency of occurrence of icing with respect to altitude could be determined from the data, since the aircraft traversed a wide range of altitudes during each flight. A histogram showing the relative frequency of icing encounters in 5000-foot-class intervals of altitude is given in figure 3. The results show that the icing encounters predominate in the low and middle cloud layers, particularly in areas where temperatures are frequently below freezing at the lower altitudes. About 70 percent of the encounters were below 10,000 feet in the Duluth area and 75 percent of the encounters were below 15,000 feet in the Seattle area. During the icing season, temperatures below freezing existed more frequently at the lower altitudes at Duluth than in the Seattle area. A rapid reduction in icing occurrence at the higher altitudes is shown in figure 3, with no icing reported while climbing or descending above 25,000 feet in either area. However, icing can exist above this altitude, as evidenced by a report of light icing occurring during cruise at 29,000 feet in another area. As noted in reference 2, the relative frequency of encountering icing in clouds is primarily a function of temperature and decreases rapidly with colder temperatures, approaching zero at -40° C.

Total-ice-accretion measurements. - The severity of icing encountered in passing through the cloud layers can be expressed in terms of the amount of ice collected on the aircraft. A reference measure of the icing severity can be determined from the cumulative ice thickness that would have formed on the sensing probe if it was not de-iced periodically. The ice formation on a small object such as the probe represents close to the maximum amount that would accumulate on any aircraft component. Substantially less ice accretion would result on larger objects with lower collection efficiencies, such as the leading edge of a wing. In this case the size of the water droplet in the clouds becomes important in determining the amount collected.

4699

The 28 encounters in which the ice accretions were measured (table II) are insufficient to give reliable statistics for evaluating the severity of icing for the climb and descent phase of high-altitude operations. The limited measurements were partly the result of encounters not being recorded by the icing-rate meters because the total accretion in passing through the cloud layers was below the threshold value of ice thickness (0.028 in.) required for initial actuation of the meters. In many encounters the thickness of the ice accretion was less than the required amount because of the short distance within the clouds resulting from steep flight angles through thin cloud layers.

The cumulative ice accretions of table II are shown in figure 4 ordered according to the number of encounters in which particular ice accretions on the probe were equalled or exceeded. These specified accretions are determined by the number of cycles of the sensing probe, thus giving ice thicknesses in multiples of 0.028 inch (adjusted to include ice that would accrete during the time of de-icing). For example, an ice accretion on the probe sufficient to cycle the probe 1 or more times (0.028 in.) was encountered 28 times during the period, whereas only one encounter cycled the probe 13 times giving an accumulative ice thickness of 0.4 inch. Generally, these accretions indicate that the maximum amount of ice formed during the climb or descent will be a relatively small value (even on small objects) when compared with amounts that can be formed during horizontal flight in icing conditions (up to 6 in. on probe reported in ref. 5).

## Calculated Probabilities of Icing Severity

In order to evaluate better the icing severity probabilities, previously measured statistics may be employed to calculate what conditions could be expected during climb and descent. The severity of icing depends essentially on the liquid-water content and vertical thickness or depth of the cloud layers. The water content probabilities can be determined on the basis of the physical process of cloud formation (adiabatic lifting), using measured frequency distributions of icing-cloud depths and temperatures. The derived probabilities can then be compared with the limited measurements of cumulative ice accretions from the fighter-interceptor aircraft operations (since the ice accretions are a function of the water concentration and of the depth of the cloud layers).

The symbols and the procedure for calculating the probability of average liquid-water content when icing is encountered during climb and descent are given in appendixes A and B, respectively. The concentration of liquid water between the base and top of a cloud layer is calculated by considering the amount of water vapor condensed by adiabatic cooling of saturated rising air. On this basis the liquid-water content increases with the height above the cloud base and with the temperature at the cloud base. To determine the ice accretion in a vertical traverse through a cloud layer, only the average water content existing between base and top needs to be calculated. Probable water contents characteristic of icing conditions were computed from frequency distributions of cloud depths and temperatures previously experienced in icing clouds. These measurements were made by airline aircraft during routine operations (ref. 5). The frequency distributions were considered as independent probabilities. The resulting probability distribution of average liquid-water content is shown in figure 5. The distribution indicates that 0.2 gram per cubic meter, for example, will be exceeded in 46 percent of the encounters, whereas 0.9 gram per cubic meter can be expected in only one icing cloud in 100.

The amount of ice collected is a function of the product of the average water content in the cloud layer and the distance traveled in passing through the cloud layer. This distance can be expressed in terms of the ratio of the airspeed $V$ (knots) to the rate of climb $C$ (ft/min). Decreasing values of this ratio $V/C$ represent steeper flight path angles and thereby shorter distances through a cloud of a given depth. The procedure for calculating the total collection on an object the size of the ice-sensing probe is described in appendix C. Probability distributions of ice accretion were computed for constant $V/C$ ratios from the frequency distribution of liquid-water content derived in appendix B and the cloud depth distribution from reference 5. The results are shown in figure 6 for a range of climb and descent conditions. The obvious advantage of reducing the distance traveled through a given cloud depth in terms of smaller values of $V/C$ can be seen in this figure. For example, if the maximum allowable accretion on a component is 1/4 inch of ice, the probability of exceeding this amount is one in four vertical traverses through an icing cloud at 160 knots and 500 feet per minute ($V/C = 0.32$); but the probability decreases to one chance in about 640 encounters if the climb conditions are increased to 240 knots and 8000 feet per minute ($V/C \approx 0.03$).

By determining the probability of encountering icing during the climb and descent phase of a flight and the probable severity once icing is encountered, the expected severity for over-all flight operations can be calculated. This icing expectancy is computed in appendix D, considing the fighter-interceptor-aircraft operations reported herein

(1200 flights per year) and combined large-scale airline operations (100,000 flights per year) representing fleets of jet transports. The results are shown in figure 7. Considering the over-all icing frequency experienced by the fighter-interceptor aircraft (5 percent of approximately 1200 flights) a 1/4-inch ice accretion could be expected to occur once in about 12,000 flights at a $V/C$ ratio of 0.03, or 14 times per year at a $V/C$ ratio of 0.32. In large-scale operations the maximum accretion would not be expected to exceed about $1\frac{1}{2}$ inches at a moderate climb angle equivalent to a $V/C$ ratio of 0.12 (240 knots at 2000 ft/min).

The limited number of cumulative ice accretions measured by the fighter-interceptor aircraft are shown plotted in the group of curves (fig. 7) representing these operations. A direct comparison of the measured data with the calculated values cannot be made because of the wide variation in $V/C$ ratios employed by the aircraft during the survey. These ratios varied between 0.05 and 0.30 with a mean of 0.17. Since the data points fall below the 0.12 curve, it may be concluded that the calculated ice accretions represent conditions in excess of what may exist. The full amount of liquid water derived from adiabatic lifting may not be generally realized, and kinetic heating may have reduced the effective amount of ice accretion from the available liquid water in the cloud layers.

## CONCLUDING REMARKS

The icing frequencies reported from the two surveyed areas can be used only as a very rough estimate of the probabilities of occurrence of icing for other locations and periods. Because of the small number of encounters, the limited period of the survey, and the sampling from only two areas, the statistical reliability of the reported frequencies is rather poor. In general, a method of estimating the probability of encountering icing for other areas would require known frequencies of cloud penetrations and conditional probabilities that icing existed in these clouds. Penetration frequencies would relate to the normal frequencies of cloud cover in a given area provided the flight path was not purposely altered to avoid clouds. The probability of icing when penetrating clouds at temperatures below freezing generally can be related to the cloud temperature, with colder clouds tending to reduce the probability of icing.

Icing clouds encountered during low-level approach procedures at the terminal phase of the flight should be considered apart from the over-all climb and descent icing problem. Depending on navigation and air traffic considerations (e.g., holding), the approach may require a flight path in icing clouds covering a relatively longer distance than that when traveling at an angle through a cloud layer. This would produce ice accretions larger than those collected during climb or descent. However, from a probability viewpoint these large accretions are less likely to occur. In climb or descent, cloud layers existing at any level in the vertical traverse will be penetrated, whereas in the low-level approach only cloud layers existing at the altitude of the approach will be encountered. The probability of encountering icing of given severity is, therefore, dependent upon the probability of the occurrence of a cloud layer of given depth, reduced by the additional probability of that cloud layer existing at a given distance above the ground. In the Duluth area, for example, the cloud bases (ceilings) reported as being below 5000 feet are such that the frequency of icing encounters within that altitude range would be only about one-seventh of the over-all frequency of icing encountered during climb and descent. The severity of the problem can be further reduced if provision is made for small changes in holding altitude to keep the flight above or below a cloud layer.

The results of this investigation show that the greater frequency of icing existing at lower levels is encountered by high-altitude aircraft during climb and descent. However, the icing severity in terms of the amount of ice accumulated will be relatively light because of the short distance flown within the cloud layers. Icing severity can become a problem when the flight plan requires longer distances within icing clouds or requires the unavoidable penetration of cumulonimbus clouds containing very high water contents.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 9, 1958

# APPENDIX A

## SYMBOLS

$C$ rate of climb, ft/min

$D$ distance traveled in icing, miles (nautical)

$D_t$ total distance traveled through cloud depth $H$, miles (nautical)

$E$ collection efficiency of probe

$H$ depth of complete cloud layer, ft

$I$ ice accretion (thickness) on ice-sensing probe, in.

$I_e$ icing expectancy (number of encounters per year with total ice accretion exceeding specified value)

$I_t$ total ice accretion through cloud layer $H$, in.

$N$ number of flights per year

$N_e$ expected number of flights necessary to exceed specified value of total ice accretion once

$P(H)$ probability of given cloud depth increment, $\Delta H$

$P_H(w_a)$ probability of given increment of $w_a$ for given cloud depth $H$

$P(e)$ probability of icing being encountered during climb and descent phase of given flight

$P(I_t)$ probability of occurrence of specified value of total ice accretion after icing is encountered during climb or descent

$P(I_{t_f})$ probability of occurrence of specified value of total ice accretion for climb and descent phase of given flight

$P(w_a)$ probability of occurrence of given increment of $w_a$

$T$ temperature of icing cloud, $^{\circ}C$

$V$ true airspeed, knots

$w$ liquid-water content, g/cu m

| | |
|---|---|
| $w_a$ | $w$ at 1/2 $H$ |
| $x_b$ | saturation mixing ratio at cloud base, g water vapor/kg dry air |
| $x_z$ | saturation mixing ratio at altitude $z$ in clouds, g water vapor/kg dry air |
| $z$ | altitude, ft |
| $\rho_I$ | density of ice accretion on probe, g/cu m |
| $\rho_z$ | density of dry air at altitude $z$ in clouds, kg/cu m |

# APPENDIX B

## CALCULATION OF PROBABILITY OF AVERAGE LIQUID-WATER CONTENT

## WHEN ICING IS ENCOUNTERED DURING CLIMB AND DESCENT

The liquid-water content of clouds is determined by the physical process of cloud formation, in which water vapor is condensed by adiabatic cooling of saturated rising air. Thus, the adiabatic process increases the water concentration with increasing height above the condensation level (or bottom) of the cloud layer. The water concentration at any point in the cloud may be greater than that obtained from condensation because of precipitation falling from above. Generally, however, the water concentration is reduced by precipitation falling out of the cloud, and by the entrainment of dry air from outside the cloud. Considering the unmodified adiabatic process, the liquid-water content available for ice formations can be calculated based on below-freezing temperatures and cloud depths that have been found to be characteristic of icing clouds.

The concentration of liquid water $w$ at altitude $z$ above a cloud base $b$ resulting from adiabatically lifted saturated air is given in terms of the saturation mixing ratios $x$ by the following equation (ref. 6):

$$w = \rho_z(x_b - x_z) \tag{B1}$$

This results in a nearly linear increase of water content with height above the cloud base. Since the saturation mixing ratio increases with temperature, the water content at any point above the base increases with increasing temperature at the cloud base. Therefore, the water content available for icing becomes a function of the temperature at the cloud base and the height of the aircraft above the cloud base. During a vertical traverse through a cloud layer the average water content can be used in determining the general severity of the icing and the total amount of ice collected. This average water content can be taken at one-half the cloud depth because of the nearly linear relation of the water content to the cloud depth.

The probability of encountering a particular average water content during climb or descent can be determined by combining the probabilities of cloud-base temperatures and cloud depth. Since these probabilities are functions of frequency distributions of these two variables, the distributions must be combined to give a probability distribution of water content. The following procedure was used to obtain this distribution.

The variation of water content in the middle of a cloud layer was calculated from equation (B1) as a function of the depth of the cloud

4699

4699

layer and the temperature at the midpoint in the cloud. The results are shown in figure 8 for below-freezing temperatures in $2^{\circ}$ C intervals. Temperatures at the cloud base were determined by assuming a pseudo-adiabatic lapse rate between the midpoint and the base of the cloud. These temperatures are used in order to relate the calculated water content to a frequency distribution of cloud temperatures measured in icing conditions. Such a frequency distribution obtained from airline data (ref. 5) is shown in figure 9. These data are considered to have been measured while the aircraft were flying at random heights above the cloud base and therefore can apply to the middle of a cloud layer. This temperature distribution establishes a corresponding distribution of water content for a given cloud depth based on the water-content values from figure 8. The results are shown in figure 10 as probability distributions of average water content for 500-foot increments of cloud depth.

To cover a range of cloud depths, the probability distributions of figure 10 must be combined using a frequency distribution of cloud depths. Such a distribution is shown in figure 11, which was also obtained from the airline data of reference 5. The probability of a given water content increment $P(w_a)$ was then computed using figures 10 and 11 in the following relation:

$$P(w_a) = \sum_{H=500}^{H=6000} \left[P_H(w_a)\right] P(H) \tag{B2}$$

The combined probability $P(w_a)$ is the product of the two probabilities if the frequency distributions of temperature and cloud depth are considered unrelated. The resulting average water-content probability in the form of a cumulative distribution curve is given in figure 5.

4699

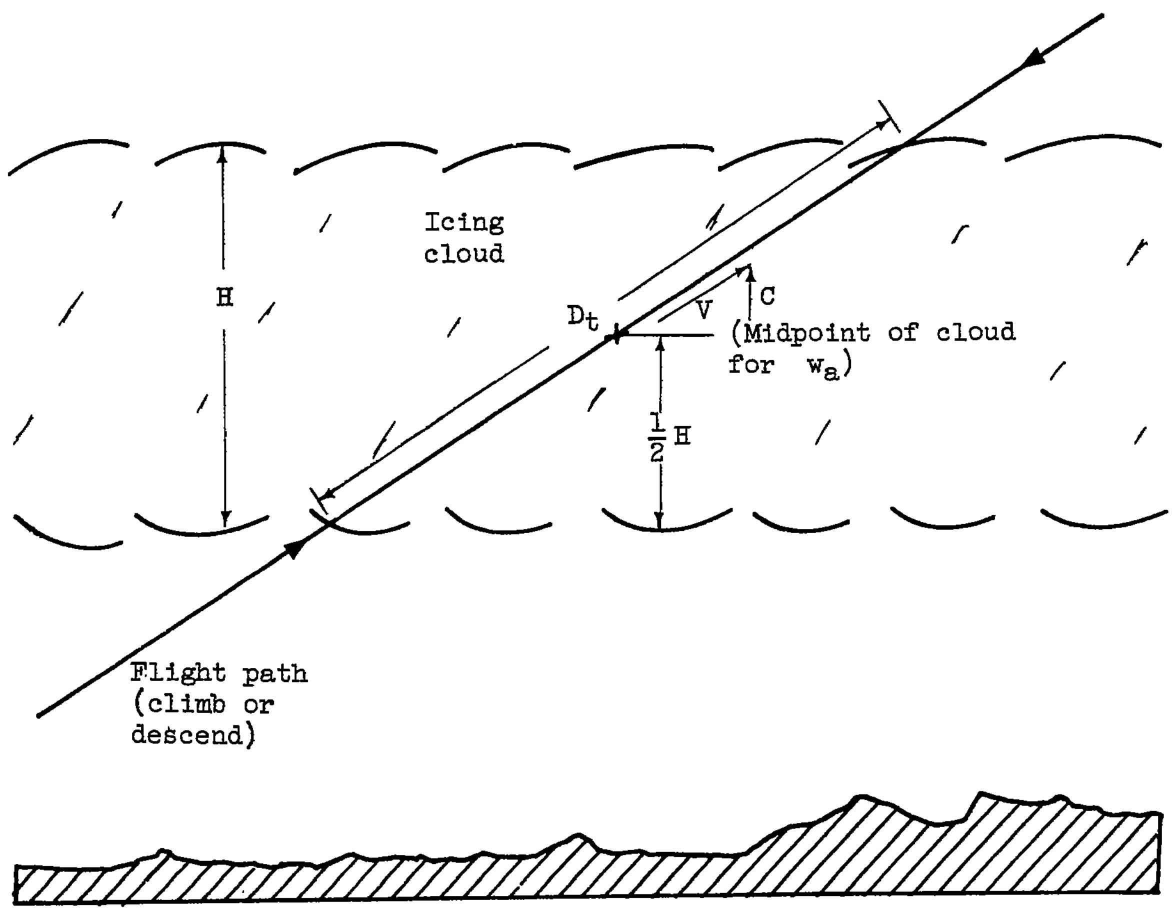
# APPENDIX C

## CALCULATION OF TOTAL ICE ACCRETION PROBABILITIES WHEN ICING IS ENCOUNTERED DURING CLIMB AND DESCENT

The amount of ice accretion I is calculated to correspond to an ice thickness that would accumulate on the icing-rate meter probe over a distance D by the relation

$$I = 0.0634 \frac{wDE}{\rho_I} \tag{C1}$$

Since the probe is only 0.1 inch in diameter, a high collection efficiency E can be assumed. The ratio $E/\rho_I$ can, therefore, be taken as approximately 1.0 (with proper units factor), which approaches the maximum ice accretion conditions for any aircraft component.



The total amount of ice accretion resulting from a climb or descent through a cloud layer is the product of an average water content $w_a$ in the cloud and the distance traveled through the cloud layer. This distance $D_t$ (as shown in sketch) can be expressed in terms of the cloud depth $H$ and the ratio of the true airspeed $V$ to the rate of climb $C$ by the relation

$$D_t = H \frac{V}{60C} \tag{C2}$$



Substituting equation (C2) in equation (C1) gives the total ice accretion $I_t$ on the probe through a cloud layer as

$$I_t = 1.056 \times 10^{-3} (w_a H)(E/\rho_I)(V/C) \tag{C3}$$

where

$$E/\rho_I = 1.0$$

The probability of encountering a particular total ice accretion in an icing cloud $P(I_t)$ at a given value of $V/C$ depends on the probabilities of given values of the product $w_a H$. Frequency distributions of total ice accretions for constant $V/C$ ratios were calculated using the distributions of $w_a$ (fig. 10) and $H$ (fig. 11) in a procedure similar to equation (B2). The resulting total ice accretion probability distribution for a range of $V/C$ ratios is shown in the form of cumulative distribution curves in figure 6.

# APPENDIX D

## CALCULATION OF ICING EXPECTANCIES FOR CLIMB AND DESCENT PHASES OF HIGH-ALTITUDE FLIGHT

The probabilities of relatively small ice accretions occurring during the climb and descent phase of any given flight $P(I_{t_f})$ can be determined by combining the probability of icing being encountered during the climb or descent phase of the flight $P(e)$ with the probability of exceeding a specified value of total ice accretion after icing is encountered $P(I_t)$; this can be expressed as

4699

$$P(I_{t_f}) = P(e)P(I_t) \tag{D1}$$

The expected number of flights necessary to exceed a specified value of total ice accretion once can be expressed as

$$N_e = \frac{1}{P(I_{t_f})} = \frac{1}{P(e)P(I_t)} \tag{D2}$$

Small probabilities can result in a significant number of actual occurrences when the over-all operation of a fleet of high-altitude aircraft is considéred in which a large number of flights per year $N$ are conducted. From this viewpoint the icing expectancy $I_e$ in terms of the number of icing encounters per year with total ice accretions exceeding a specified amount can be considered for over-all aircraft operations. This can be calculated from the relation

$$I_e = N/N_e = NP(e)P(I_t) \tag{D3}$$

This over-all operational probabilitiy of total ice accretions is shown in figure 7 for a range of climb and descent conditions considering aircraft operations involving 1,200 and 100,000 flights per year with an icing encounter probability $P(e)$ of 0.05. The particular operation involving 1200 flights per year represents the operation of the instrumented fighter-interceptor aircraft, whereas 100,000 flights per year may represent combined large-scale airline operations of a fleet of jet transports.

# REFERENCES


1. Lewis, William, and Bergrun, Norman R.: A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States. NACA TN 2738, 1952.

2. Perkins, Porter J., Lewis, William, and Mulholland, Donald R.: Statistical Study of Aircraft Icing Probabilities at the 700- and 500-Milibar Levels over Ocean Areas in the Northern Hemisphere. NACA TN 3984, 1957.

3. Jones, Alun R., and Lewis, William: Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment. NACA TN 1855, 1949.

4. Perkins, Porter J., McCullough, Stuart, and Lewis, Ralph D.: A Simplified Instrument for Recording and Indicating Frequency and Intensity of Icing Conditions Encountered in Flight. NACA RM E51E16, 1951.

5. Perkins, Porter J.: Statistical Survey of Icing Data Measured on Scheduled Airline Flights over the United States and Canada from November 1951 to June 1952. NACA RM E55F28a, 1955.

6. Lewis, William: Meteorological Aspects of Aircraft Icing. Compendium of Meteorology, Am. Meteorological Soc., 1951, pp. 1197-1203.

TABLE I. - SUMMARY OF ICING DATA FOR CLIMB AND DESCENT OF JET-FIGHTER INTERCEPTOR AIRCRAFT

| Data groups | Months | Duluth (Aug. 1955 - June 1956) | | | | | | Seattle (Nov. 1955 - Sept. 1956) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total number of - | | | Frequency of - | | Frequency of icing in clouds penetrated | Total number of - | | | Frequency of - | | Frequency of icing in clouds penetrated |
| | | Flights | Clouds penetrated | Icing encounters | Clouds penetrated | Icing encounters | | Flights | Clouds penetrated | Icing encounters | Clouds penetrated | Icing encounters | |
| 1 | June<br>July<br>Aug.<br>Sept. | 55 | 5 | 0 | 0.09 | 0 | 0 | 390 | 69<br>(May included) | 11 | 0.18 | 0.03 | 0.16 |
| 2 | May<br>Oct. | 168 | 16 | 8 | 0.10 | 0.05 | 0.50 | (Insufficient number of flights) | | | | | |
| 3 | Mar.<br>Apr.<br>Nov. | 176 | 50 | 16 | 0.28 | 0.09 | 0.32 | 146 | 31 | 10 | 0.21 | 0.07 | 0.32 |
| 4 | Dec.<br>Jan.<br>Feb. | 95 | 22 | 4 | 0.23 | 0.04 | 0.18 | 144 | 21 | 10 | 0.15 | 0.07 | 0.48 |
| | Totals | 494 | 93 | 28 | 0.19 | 0.06 | 0.31 | 680 | 121 | 31 | 0.18 | 0.05 | 0.26 |
| Totals both areas | | 1174 | 214 | 59 | 0.18 | 0.05 | 0.28 | | | | | | |

TABLE II. - ENCOUNTERS WITH MEASURED ICE ACCRETIONS

| Cumulative ice accretion, in. | Temperature, °C | True airspeed, mph | Pressure altitude of icing, ft | Rate of climb or descent, ft/min (a) | Cloud type | Pilot remarks | Date | | | Location |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Month | Day | Time | |
| 0.028 | -9.3 | 402 | 6,100 | 1200 (c) | | ------ | 3 | 21 | 1850 | |
| | -15.4 | 314 | 9,400 | 3100 (d) | Stratus | ------ | 4 | 23 | 1348 | |
| | -10.8 | 474 | 20,400 | 5000 (d) | | ------ | 4 | 24 | ---- | Duluth |
| | -11.9 | 429 | 10,200 | 7100 (c) | Stratocumulus | ------ | 4 | 16 | 0940 | |
| | -15.8 | 332 | 6,800 | 1000 (c) | ------ | ------ | 4 | 20 | ---- | |
| | -23.3 | 504 | 25,500 | ---- (c) | Cirrostratus | ------ | 11 | 29 | 2135 | Columbus, N. Mex. |
| | -7.9 | 335 | 4,800 | ---- (d) | Stratocumulus | ------ | 11 | 30 | 1615 | Portland, Oreg. |
| | -1.2 | 130 | 900 | ---- (c) | ------ | ------ | -- | -- | ---- | |
| | -11.2 | 271 | 4,900 | ---- (d) | ------ | ------ | -- | -- | ---- | |
| | -16.3 | 345 | 14,900 | 6100 (d) | Stratus | Slight icing | 2 | 1 | 0930 | |
| | -9.9 | 404 | 7,500 | 1200 (c) | Stratus | Light icing | 2 | 12 | 0100 | |
| | ----- | --- | ------ | ---- (d) | ------ | ------ | -- | -- | ---- | |
| | -12.8 | 394 | 19,000 | ---- (c) | ------ | ------ | -- | -- | ---- | Seattle |
| | -21.6 | 440 | 20,000 | ---- (d) | ------ | ------ | -- | -- | ---- | |
| | -7.2 | 417 | 6,900 | 1200 (c) | Stratocumulus | ------ | 3 | 26 | 1905 | |
| | -15.5 | 470 | 13,300 | 1900 (c) | ------ | ------ | 3 | 27 | 1855 | |
| | -4.4 | 346 | 11,700 | 2200 (d) | Cumulus | ------ | 4 | 3 | 1340 | |
| | -2.7 | 285 | 4,800 | 1800 (d) | Cumulus | Light icing | 1 | 5 | 1500 | |
| 0.059 | -11.8 | 364 | 9,900 to 9,000 | 3100 (d) | Stratocumulus | ------ | 4 | 16 | ---- | Duluth |
| | ----- | --- | 5,000 | ---- (d) | | Iced windshield | 3 | 19 | 1010 | |
| | -9.1 to -6.6 | 350 | 6,100 to 4,300 | 1200 (d) | Stratus | Light icing | 2 | 12 | 0100 | Seattle |
| | -11.1 to -8.1 | 350 | 6,100 to 3,100 | 1300 (d) | | ------ | 2 | 12 | 1115 | |
| | -11.9 | 290 | 13,300 | ---- (d) | Cumulus | Picked up frost | 11 | 1 | 1008 | |
| 0.090 | ------ | --- | 17,000 | -------- | Cumulus | Very light ice | 4 | 9 | 0800 | Duluth |
| | -12.6 to -11.6 | 329 | 11,000 to 9,200 | 3600 (d) | Stratocumulus | ------ | 4 | 16 | 0940 | |
| 0.152 | -15.4 to -10.9 | 324 | 11,300 to 9,100 | 1200 (d) | Cumulus | 1/2 in. rime ice on wings; engine ice noted | 5 | 3 | 1431 | Duluth |
| | -15.1 to -9.1 | 318 | 9,000 to 5,400 | 1100 (d) | Stratus | ------ | 2 | 12 | 1455 | Seattle |
| 0.400 | -10.7 to -16.2 | 418 | 11,300 to 14,500 | 1000 (c) | Stratus | Moderate rime ice | 1 | 20 | 0945 | Seattle |

[a]Climb, c; descent, d.

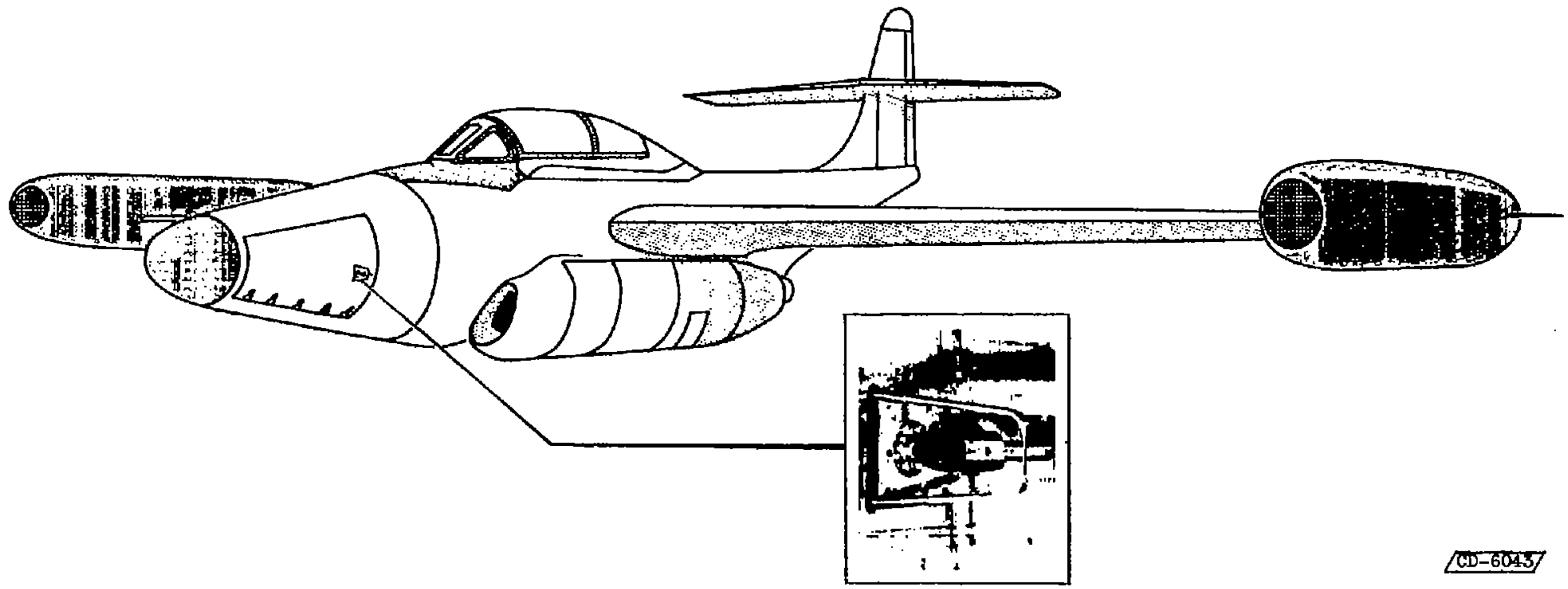



Figure 1. - Location of ice-sensing probe on fighter-interceptor aircraft.

PROJECT ICE
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
LEWIS FLIGHT PROPULSION LABORATORY
21000 BROOKPARK RD
CLEVELAND 35, OHIO

ICING DATA SHEET

Please Note: These data supplement measurements of atmospheric conditions being film recorded by NACA icing meter in the aircraft. Meter automatically starts upon encountering icing (Recording light-green), and stops 10 minutes after end of icing rate cycle (Icing rate light-amber). In order to utilize the recorded information, this form must be properly filled out for each flight regardless of whether icing conditions were encountered.

Organization ______________________

Pilot ______________________

Aircraft No. ______________________

Date of Flight 21 Mar.

Take off Time (local) 1850

Duration of Flight 1 hrs 30 min

Was icing encountered Yes ☑ No ☐

Altitude of icing 3500 to 5000 ft

Cloud Type Stratus

Duration of Recorder Operation 30 sec

Remarks: Green light was on about 30 sec, Amber for only 10 to 12 sec.

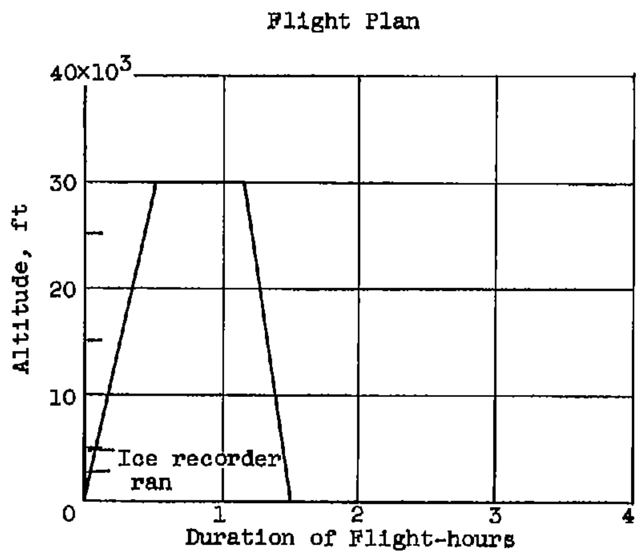
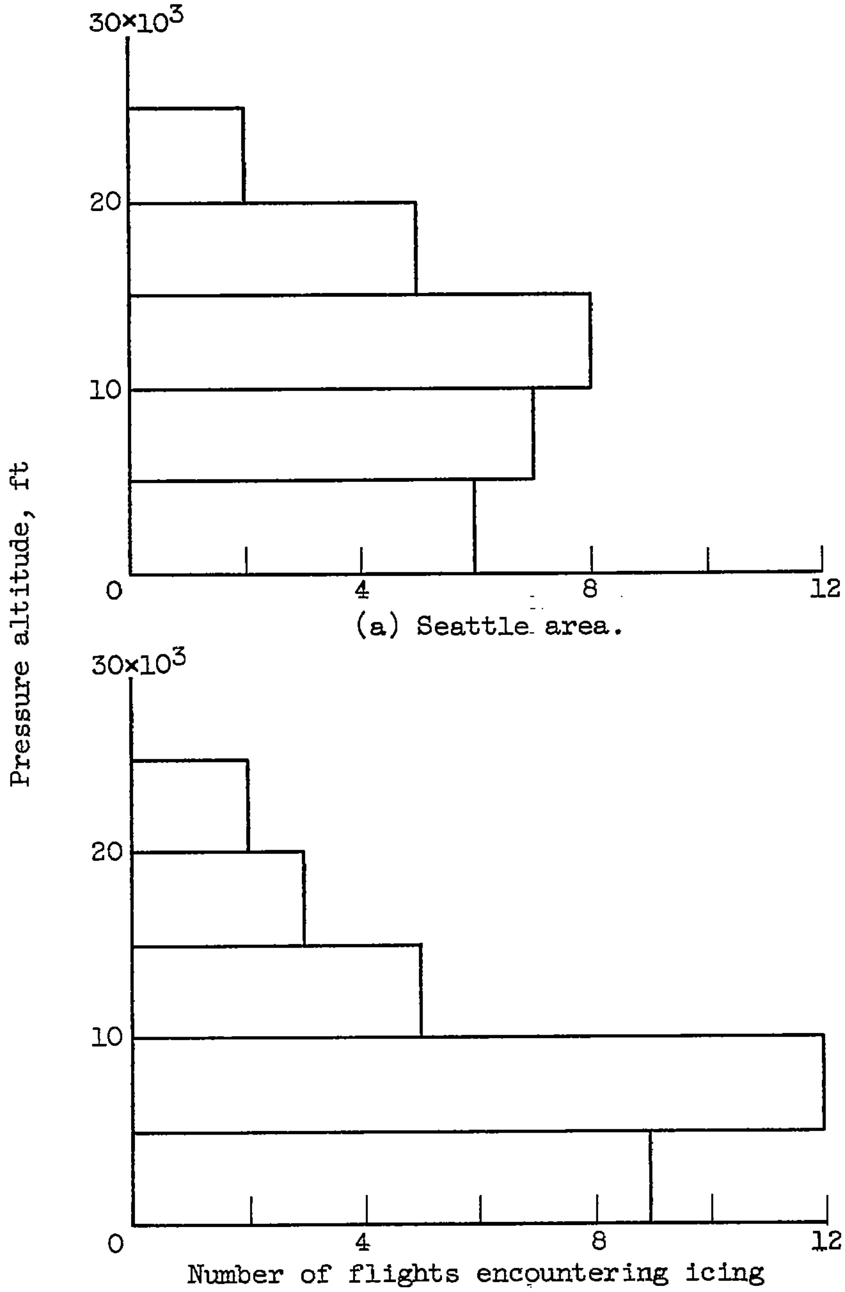



Figure 2. - Sample of special log sheet supplied to supplement recorded data.




(b) Duluth area.

Figure 3. - Histogram of altitude distribution of icing encountered during climb and descent.

4699

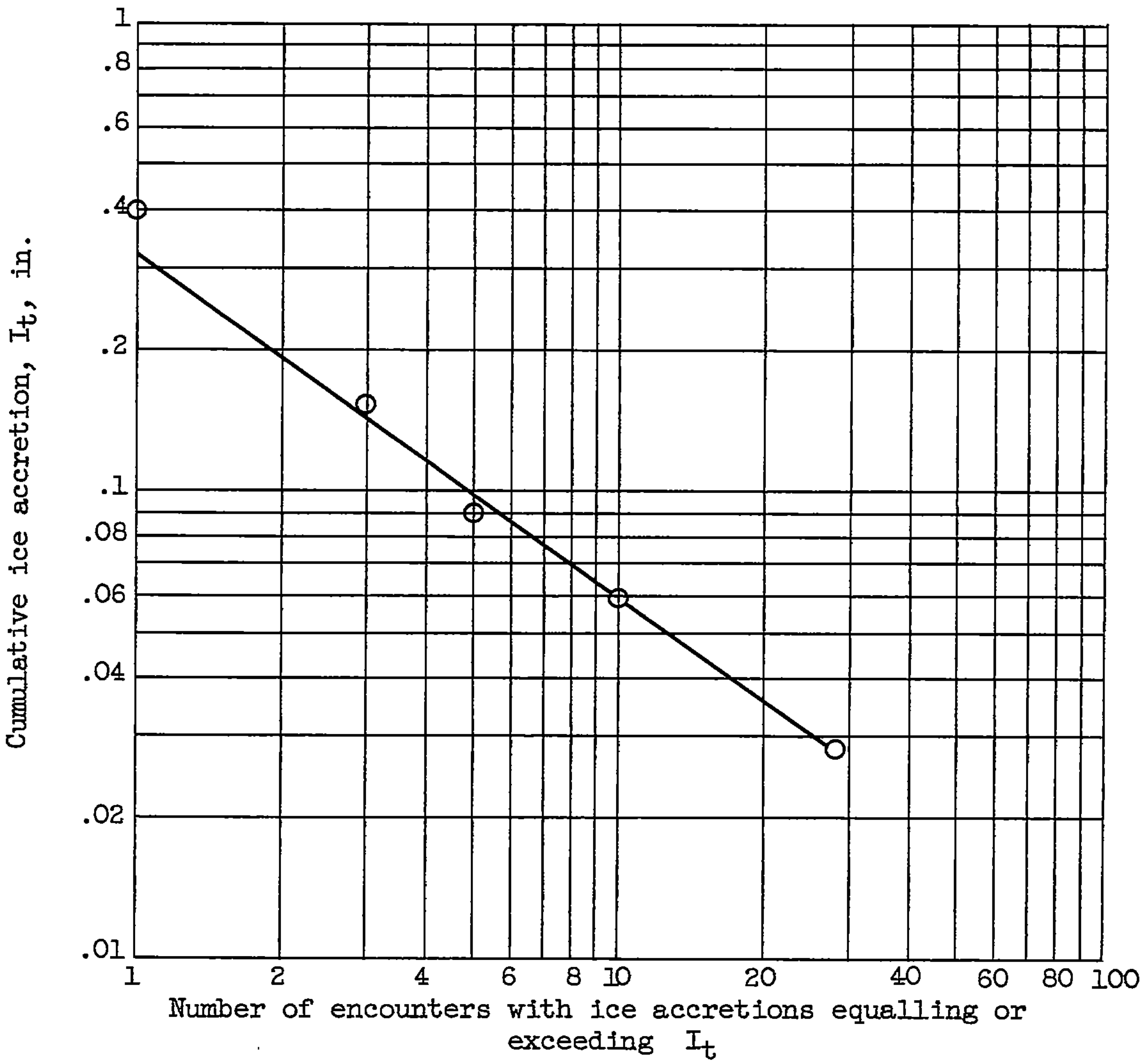



Figure 4. - Cumulative ice accretions measured on sensing probe during climb and descent arranged according to number of encounters in which particular ice accretion values were equalled or exceeded.

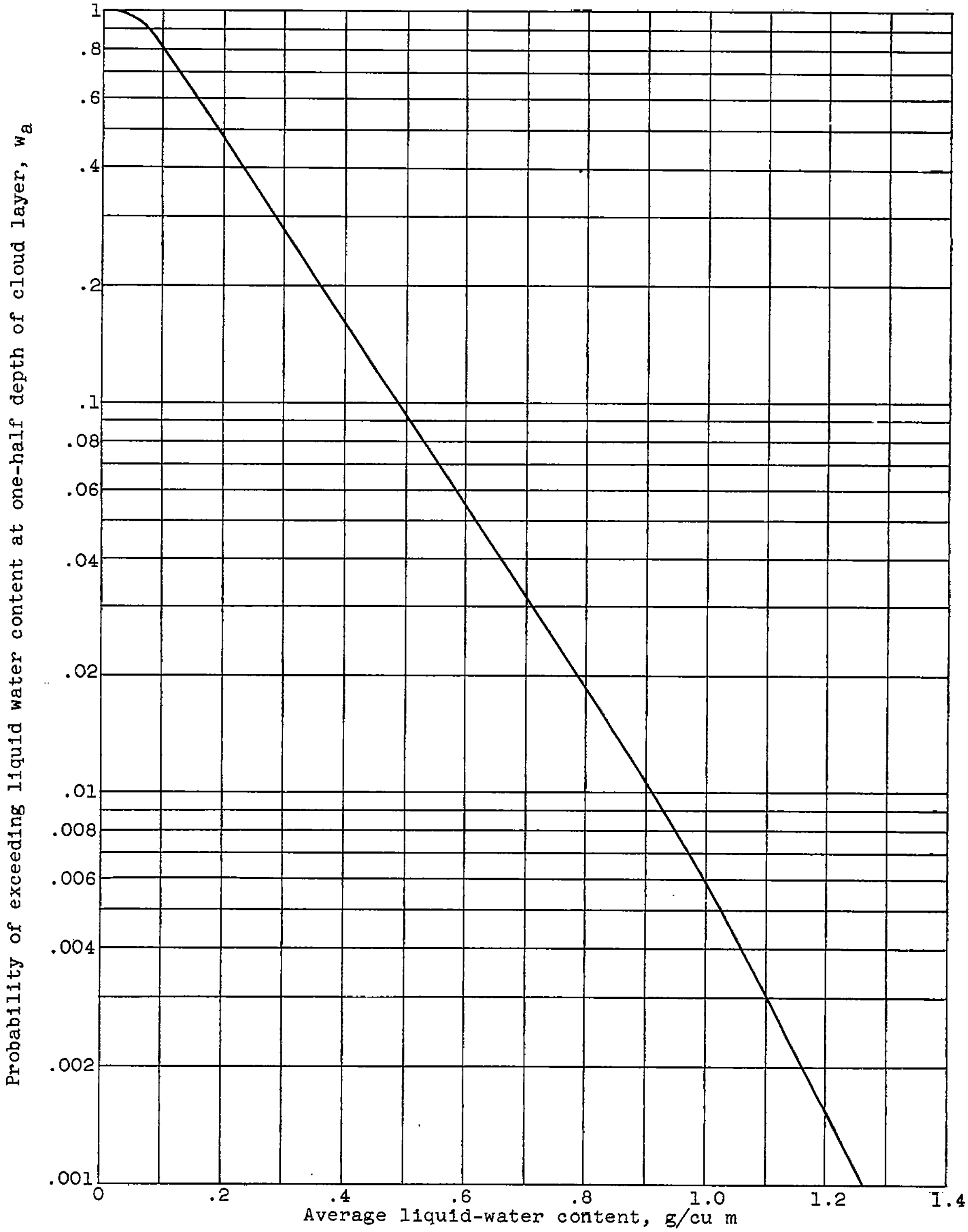



Figure 5. - Probability distribution of average liquid-water content based on adiabatic lifting in icing clouds encountered during climb or descent.

4699

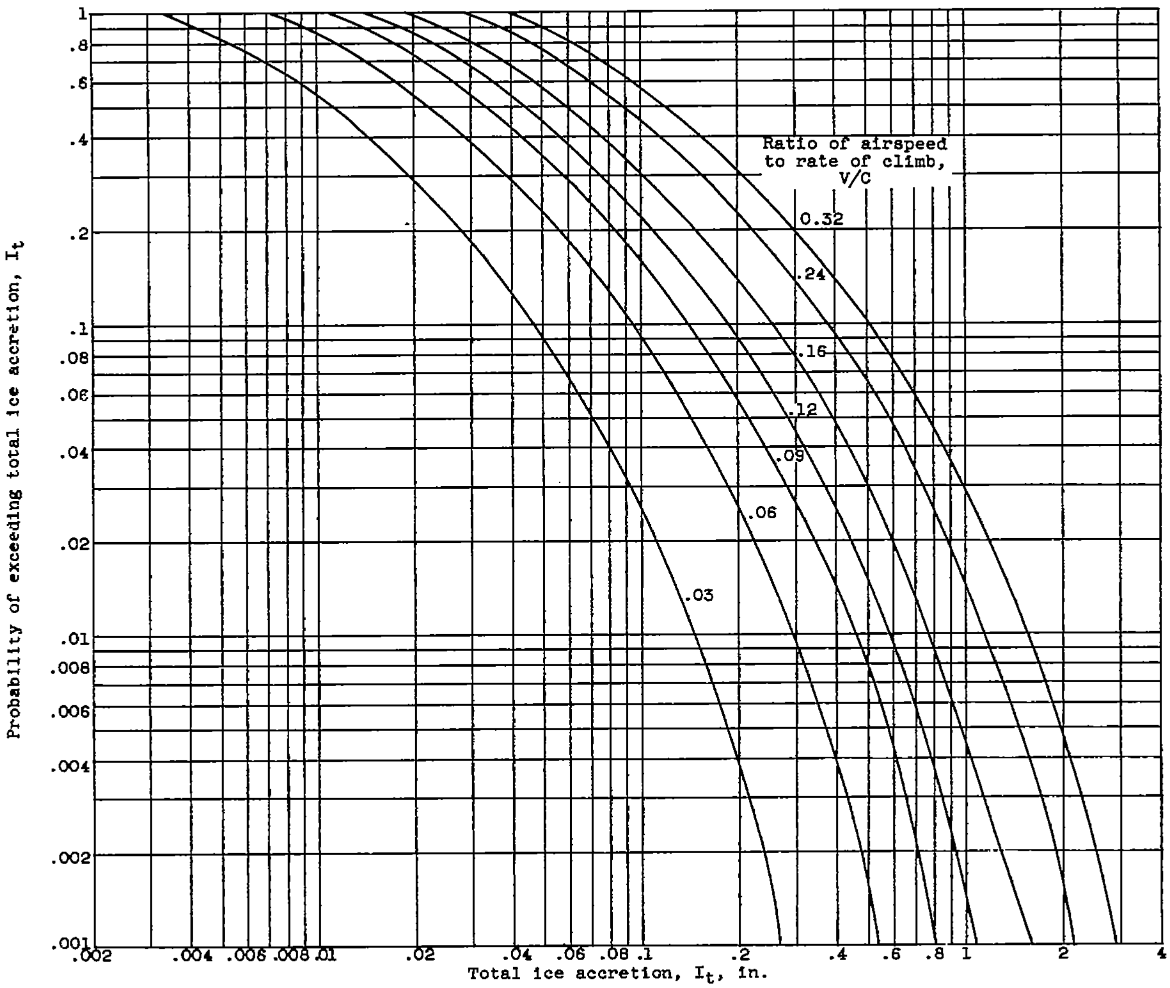



Figure 6. - Probability distribution of total ice accretion on ice-sensing probe for range of climb and descent conditions.

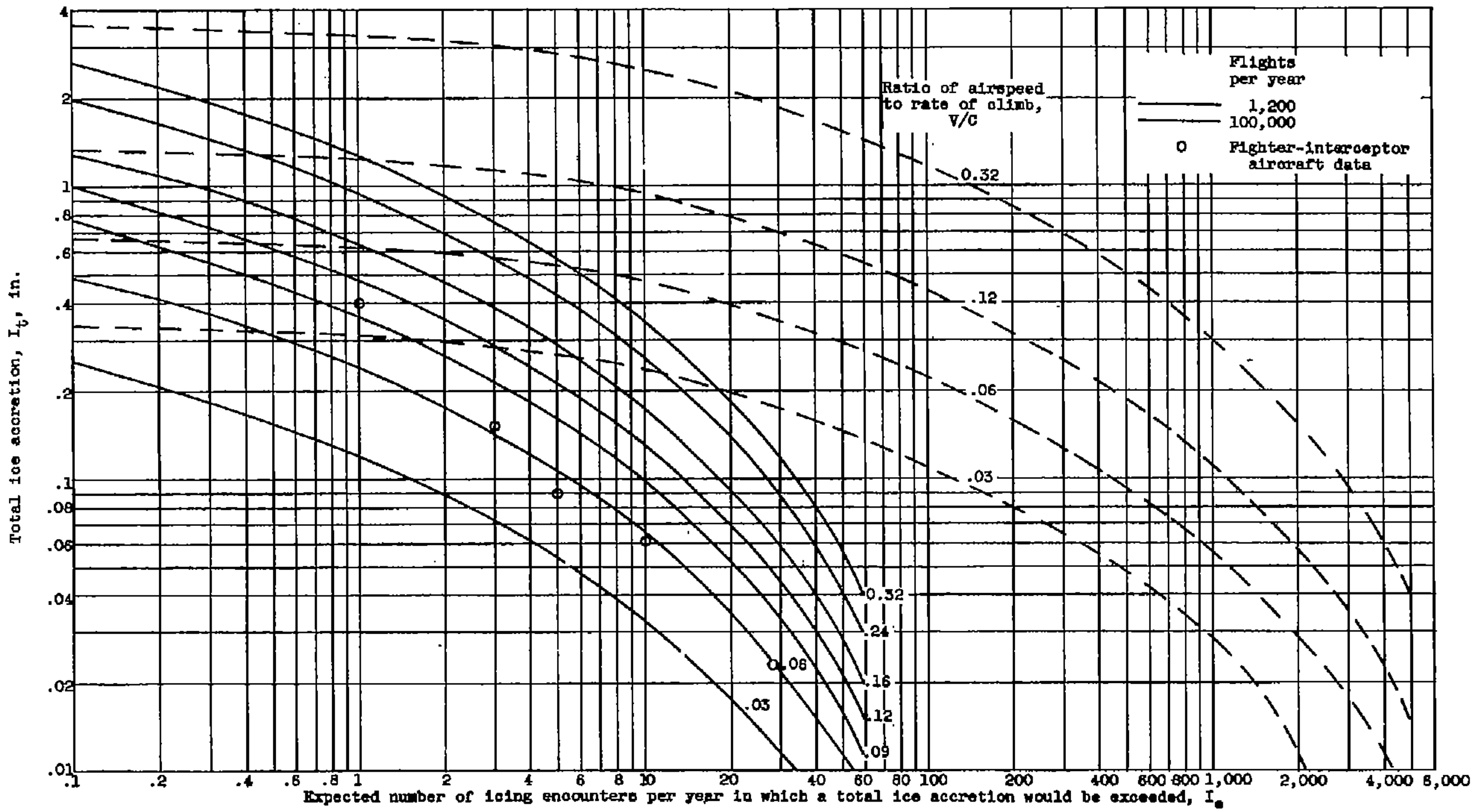



Figure 7. - Operational probability of total ice accretion on ice-sensing probe for range of climb and descent conditions. Icing frequency, 0.05.

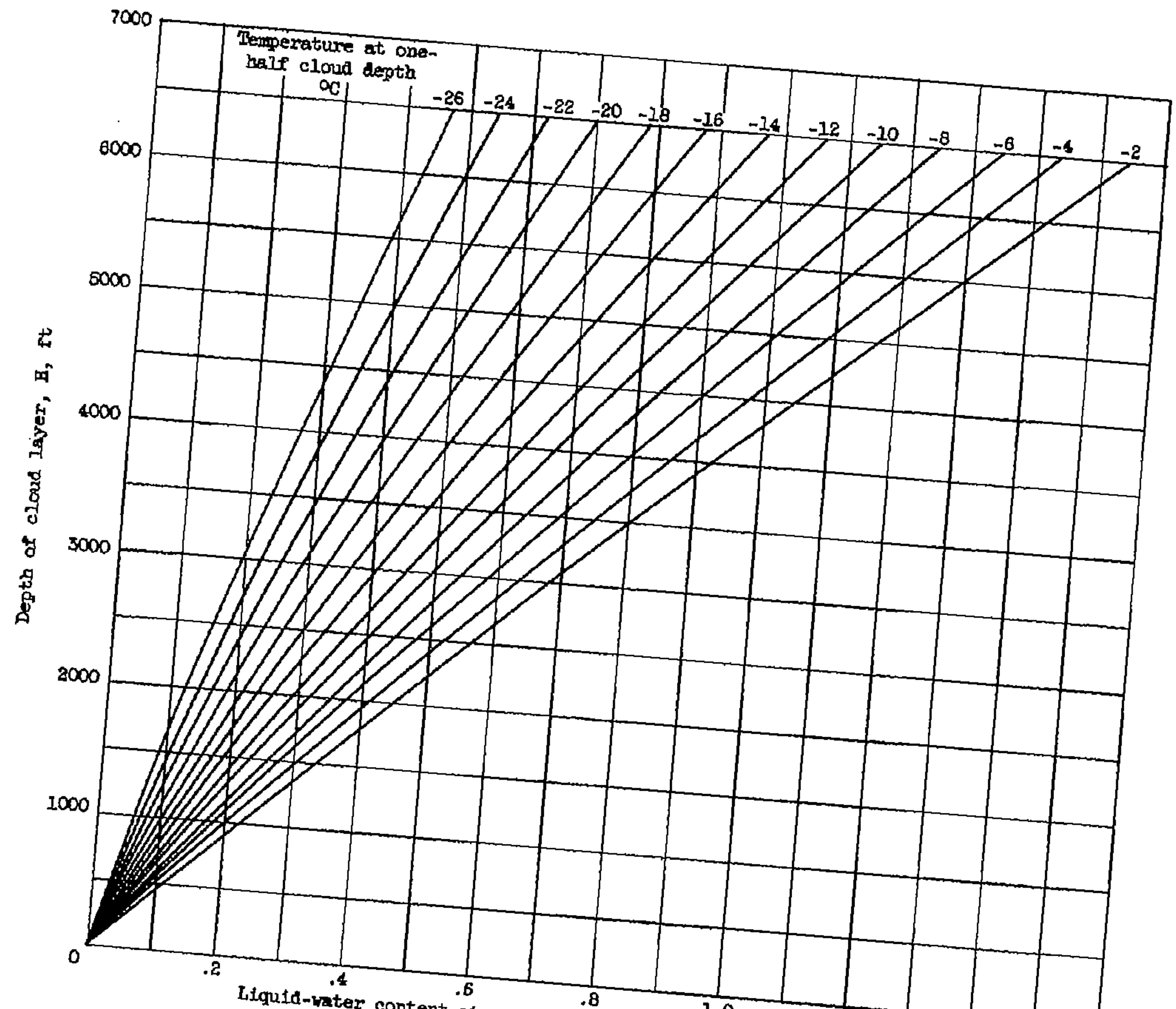



Figure 8. - Variation of liquid-water content in middle of cloud with depth of cloud layer and temperature of cloud at one-half cloud depth (based on adiabatic lifting).

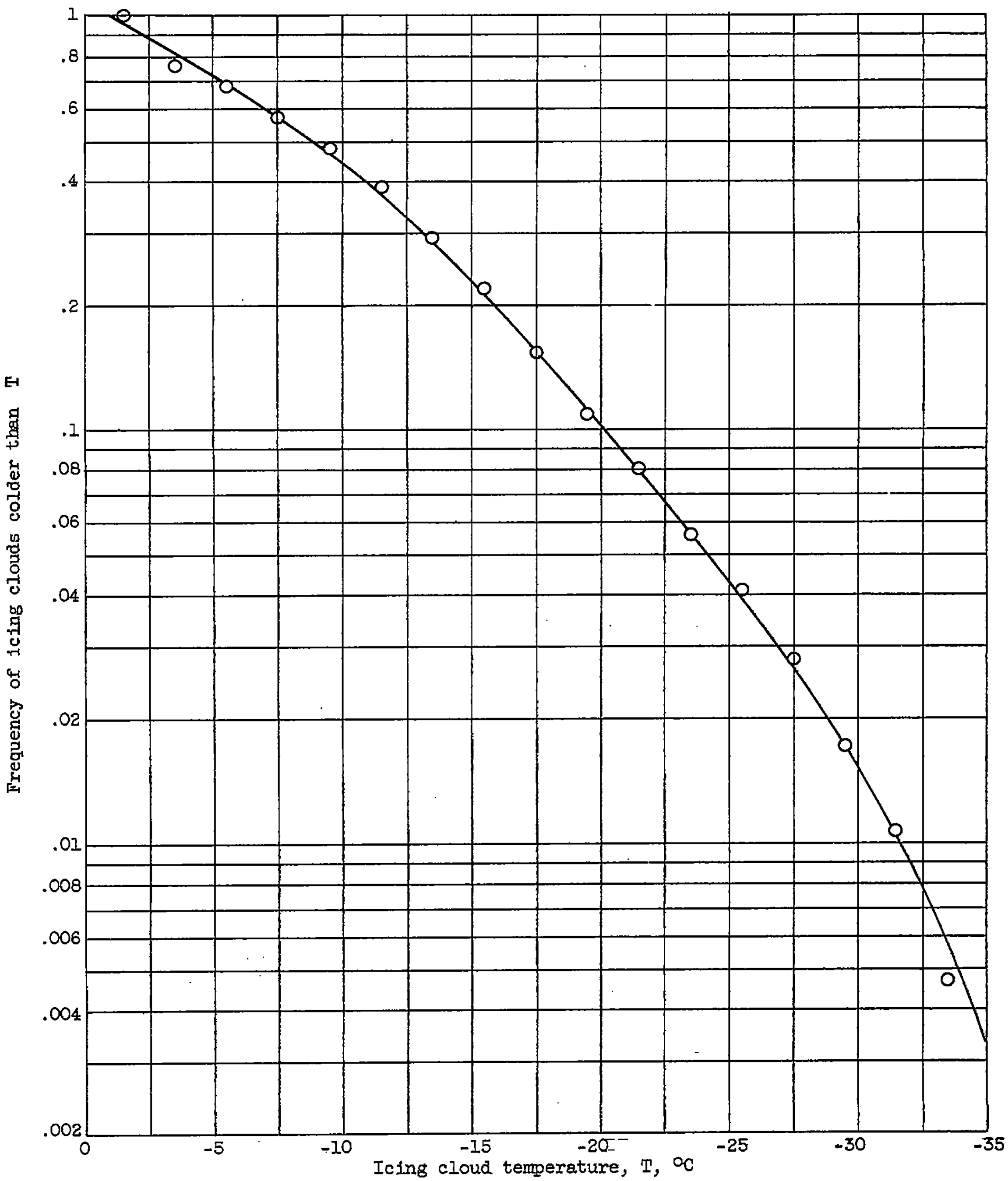



Figure 9. - Cumulative frequency distribution of temperatures of icing clouds.

4699

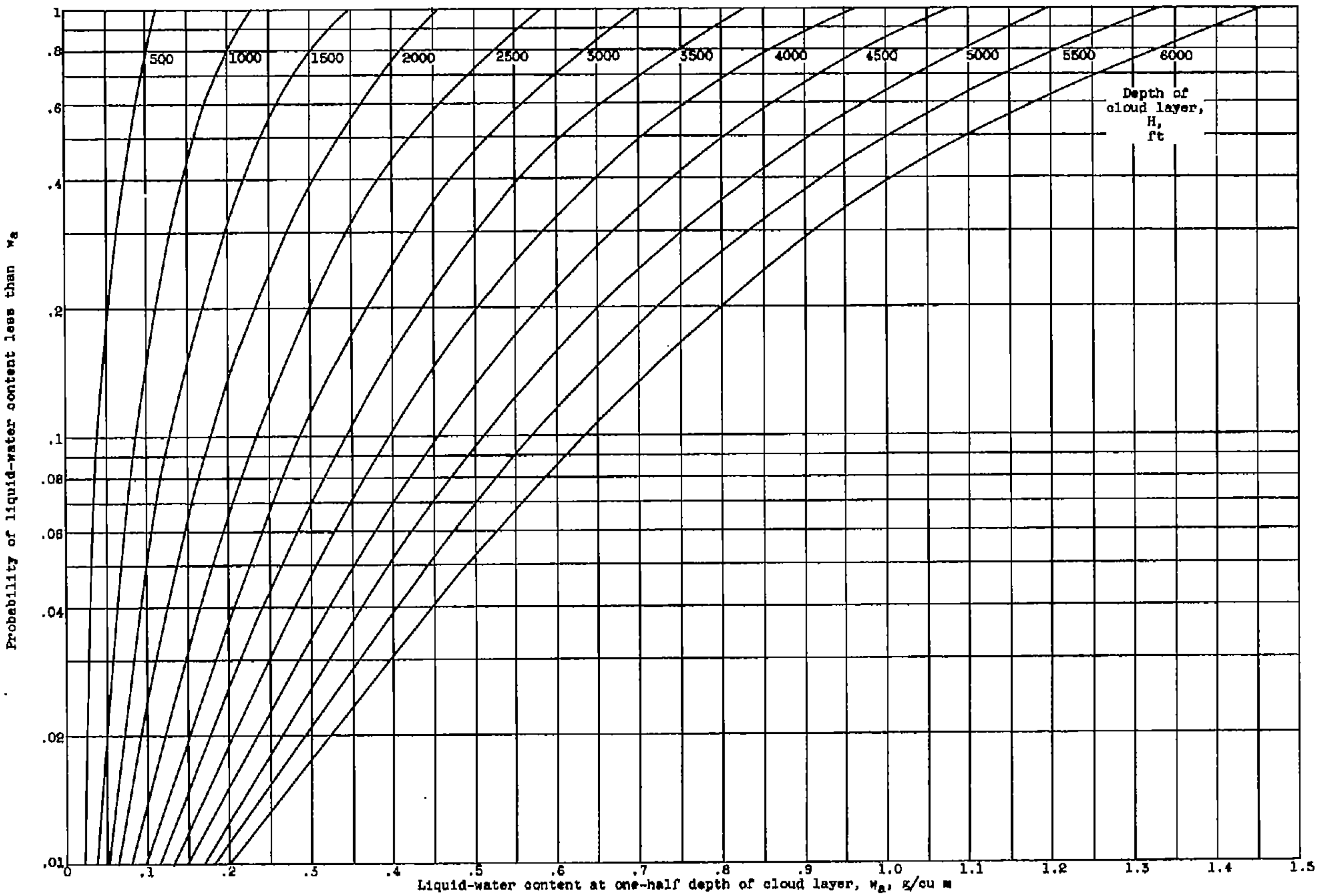



Figure 10. - Probability distributions of liquid-water content in middle of cloud based on temperature distribution of figure 9 for several cloud depths.

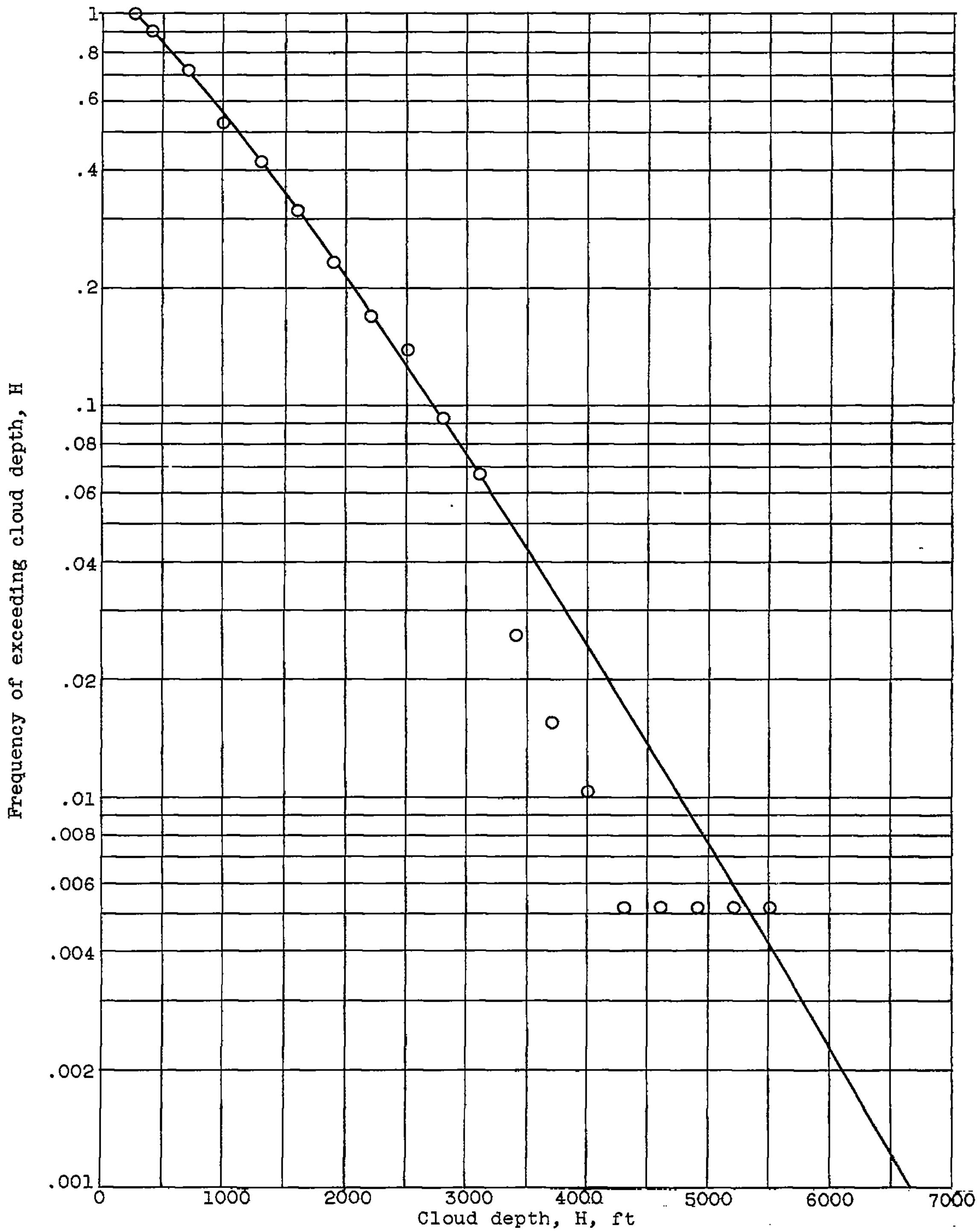



Figure 11. - Cumulative frequency distribution of depth of an icing cloud layer